

Interaction effects at the magnetic-field induced metal-insulator transition in Si/SiGe superlattices

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A metal-insulator transition was induced by in-plane magnetic fields up to 27 T in homogeneously Sb-doped Si/SiGe superlattice structures. The localisation is not observed for perpendicular magnetic fields. A comparison with magnetoconductivity investigations in the weakly localised regime shows that the delocalising effect originates from the interaction-induced spin-triplet term in the particle-hole diffusion channel. It is expected that this term, possibly together with the singlet particle-particle contribution, is of general importance in disordered n-type Si bulk and heterostructures.

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Due to the sensitivity to external perturbations and the possibility of controlling the randomness, doped semiconductors and semiconductor structures have proven to be excellent media to examine the nature of localisation in disordered electronic systems.^{1–3} In particular, the remarkable studies⁴ of bulk Si:P have demonstrated that the doping-induced metal-insulator transition is continuous, and that the effects of backscattering and disorder-modified electron-electron interaction are equally important at the localisation boundary. The latter was confirmed by investigations⁵ of interfacial electron layers in Si MOS-FETs, which indicate that all states are localised in disordered two-dimensional (2D) systems.⁶ While the corresponding theoretical predictions have found detailed quantitative verifications in a number of experimental studies on various semiconductor compounds and disordered metals, the case of n-Si,⁷ and more recently of high mobility Si MOS-FETs,⁸ have demonstrated unsatisfactory understanding of the Si-based systems. Extensive theoretical studies³ re-emphasise the peculiar properties of n-Si, where the weakness of spin-dependent scattering – associated with the lightness of the constituting atoms, the presence of inversion symmetry in the diamond lattice, and the low degree of compensation – makes the anti-localising interaction terms in the conductivity corrections particularly large.

Even more surprising are perhaps the results by Kravchenko et al.,⁸ which point to the existence of a metallic phase in high electron-mobility Si MOS-FETs at zero magnetic field. Several suggestions on the origin of this unforeseen metallic phase in that 2D system have been put forward: (i) Coulomb interactions of re-

mote electrons,⁹ (ii) superconductivity due to spin-triplet pairing,¹⁰ (iii) non-Fermi liquid behaviour driven by effects of electron-electron interactions,¹¹ and (iv) the existence of a spin-orbit gap due to a strongly asymmetric confining potential in Si-MOS structures.¹² In most recent experimental works^{13,14} the suppression of the low temperature conducting phase by an in-plane magnetic field was demonstrated, which indicates the importance of spin-related terms.

Here, we report about millikelvin studies of in-plane conductivity up to magnetic fields of 27 T for uniformly Sb-doped Si/SiGe superlattices (SLs). In our Si/SiGe SLs, the six fold valley degeneracy of the Si conduction band is removed due to the biaxial strain. For the two ground state valleys the in-plane effective mass is nearly by a factor of 5 smaller than the longitudinal mass. The vertical transport mobility is in addition strongly reduced by the weak coupling through the SiGe barriers, resulting in a rather large anisotropy of electron transport. At the same time, the electron Landé factor is expected to be isotropic and close to its value in bulk n-Si, $g^* = 2.0$. Accordingly, the magnetoresistance studies, which we carried out for the two orientations of the magnetic field with respect to the SL interfaces, make it possible to determine the relative importance of the orbital and spin effects. Our results confirm that electron delocalisation in Si-based materials at the metal-insulator transition (MIT) is driven by spin-dependent phenomena. We assign these phenomena to the presence of anti-localisation terms in the quantum corrections to the conductivity of disordered systems. In the absence of spin-orbit coupling, such spin-dependent terms may arise from the triplet particle-hole and singlet particle-particle diffusion channels of the disorder-modified electron-electron interactions.^{1,15}

The SL structures were grown by MBE on (001) Si substrates with a SiGe graded buffer layer. Each of the SLs consist of 150 periods of Si wells ($d_w = 25$ Å) and Si_{0.55}Ge_{0.45} barriers ($d_b = 14$ Å). The impurity densities in our samples, $\tilde{N} \equiv N/10^{18} \text{ cm}^{-3} = 2.5, 4.5$, and 6, cover the range around the critical concentration of $\tilde{N} = 3$ for the MIT in bulk Si:Sb.¹⁶ The structural properties of the SLs were determined by high resolution x-ray diffraction, whereas the Ge and Sb concentrations and their homogeneity were checked by secondary ion mass spectroscopy. Resistivity and Hall effect measurements between 10 and 300 K show only a small change of the Hall constant with temperature, and lead to an

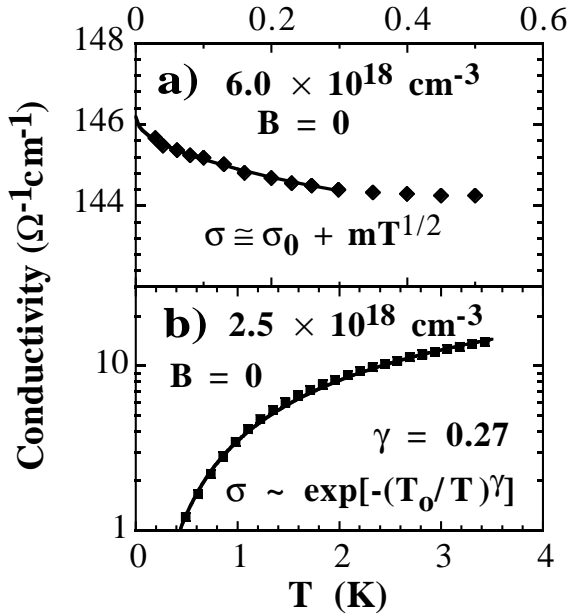


FIG. 1. In-plane conductivity of Si/SiGe:Sb superlattices with (a) $N = 6 \times 10^{18} \text{ cm}^{-3}$, and (b) $2.5 \times 10^{18} \text{ cm}^{-3}$ as a function of temperature in zero magnetic field. Solid lines represent fitting to formulae corresponding to metallic (a) and hopping conduction (b), respectively.

agreement between electron densities and Sb doping levels within 5%.

Previous investigations of our structures, carried out in the magnetic fields up to 9 T, have demonstrated that electron conductivity retains features of 3D transport, despite that the miniband width w is more than 10 times smaller than the in-plane momentum relaxation rate \hbar/τ .¹⁷ In particular, the magnetoconductivity at 1.5 K in the weakly localised regime can be described by the theory for a disordered 3D electronic system with an anisotropic diffusion tensor.^{1,18,19}

The present magnetoresistance studies were carried out in a dilution refrigerator, installed either in a superconductive 9 T coil or in a hybrid magnet capable of 27 T. It has been found in the course of this work that the temperature (and phase coherence) of the conducting electrons in the studied structures are strongly affected by high frequency electromagnetic noise. It appears that the electrons in Si/SiGe are less resistant to electron heating than in zinc-blend compounds. In the latter, the piezoelectric coupling, due to its energy loss rate which is proportional to $T_e^3 - T_l^3$, results in better electron cooling than that in the elemental semiconductors, in which only the interaction by deformation potential, characterised by $T_e^5 - T_l^5$ -dependence, is effective at low temperatures.²⁰ Here T_e denotes the electron and T_l the lattice temperature.

In Fig. 1, the temperature dependence of the in-plane conductivity is shown for two Si/SiGe SLs at zero magnetic field. For the highest doping level ($\tilde{N} = 6$) an increasing conductivity with decreasing temperature is

observed (Fig. 1a). This metallic behaviour is well described by the dependence $\sigma(T) = \sigma_0 + mT^{1/2}$, where $m < 0$. The lowest doped SL with $\tilde{N} = 2.5$ shows (Fig. 1b), in turn, a strong drop of the conductivity on decreasing temperature, which can be described by $\sigma \propto \exp(-(T_0/T)^\gamma)$ with $\gamma = 0.27 \pm 0.05$. This dependence points to a variable-range hopping conductivity, and thus shows that the sample is on the insulator side of the MIT. Here, $1/4 \leq \gamma \leq 1/2$ is expected for 3D systems, depending on the shape of the Coulomb gap.²¹ The temperature dependence of the conductivity in the absence of a magnetic field proves, therefore, the presence of the doping-induced MIT in the Si/SiGe:Sb SL system. Moreover, the observed increase of the conductivity at the lowest temperature demonstrates that in the highest doped sample the anti-localisation interaction terms dominate over other quantum corrections to the conductivity.

Results of detailed low-temperature conductivity studies of the $\tilde{N} = 4.5$ SL up to magnetic fields of 27 T are presented in Fig. 2. The orientation of the magnetic field was chosen to be either parallel (Fig. 2a) or perpendicular (Fig. 2b) to the SL layers. In both cases the measurement current was perpendicular to the magnetic field. In the case of sufficiently strong parallel magnetic fields, the in-plane conductivity (inverse in-plane resistivity) σ extrapolated to zero temperature vanishes in the $T^{1/2}$ presentation of Fig. 2a, and thus shows a magnetic-field induced MIT. For σ , a $T^{1/2}$ dependence, characteristic for 3D systems in the magnetic field,^{4,7,16,22} is visible over a wide temperature and field range. However, because the quantum corrections to the conductivity of anisotropic systems are proportional to the ratio of the diffusion constant along the current to the average one,¹ the magnitude of $d\sigma/dT^{1/2}$ in n-Si/SiGe SLs at criticality is found to be by about a factor of 8 greater than in bulk n-Si.^{7,16,22} This makes the extrapolation to $T = 0$ unusually inaccurate in our system and precludes an accurate determination of the critical magnetic field. In contrast to the $\tilde{N} = 4.5$ sample, the $\tilde{N} = 6.0$ sample does not show a MIT in the magnetic field. The extrapolated zero- T conductivity σ decreases gradually with the in-plane magnetic field but remains non-zero up to 27 T.

In the case of perpendicular geometry (Fig. 2b) the decrease in conductivity with increasing magnetic field is much weaker than for the parallel orientation, so that no MIT is observed. The extrapolated zero- T value of σ does not vanish up to 12 T for the $\tilde{N} = 4.5$ SL. For higher magnetic fields, however, the conductivity does not decrease monotonically any more. Accordingly, this region is not displayed in Fig. 2b as the overlapping curves would not give a clear picture. As shown in the inset of Fig. 2b, in the range of high perpendicular magnetic fields, the resistivity exhibits a broad minimum around 21 T which is consistent with a Shubnikov-de Haas oscillation or a quantum Hall state at a filling factor $\nu = 4$. The occurrence of quantum Hall states is possible in the case

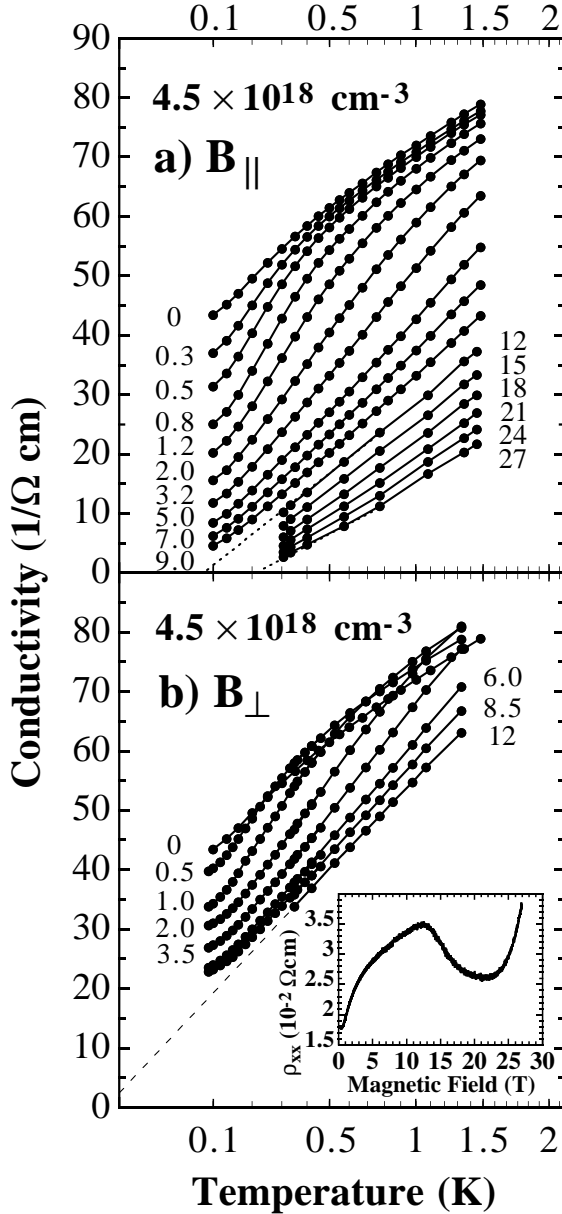


FIG. 2. Conductivity of Si/SiGe:Sb superlattice with $\tilde{N} = 4.5$ in various magnetic fields (a) parallel and (b) perpendicular to the layers as a function of temperature in $T^{1/2}$ scale. The dashed lines are guides for the eye. The inset in (b) shows the magnetic-field dependence of the resistivity for the perpendicular orientation.

of weakly coupled wells in a superlattice structure.^{23,24} The existence of quantum Hall plateaux could not, however, be proved in our structures, as the Hall voltage is much smaller than the longitudinal voltage in these low mobility samples.

We note that the occurrence of the transition for B parallel to the interface planes (Fig. 2a), and its absence in the perpendicular configuration (Fig. 2b) proves rather directly that the field-induced MIT in n-Si^{7,16,22} is driven by a spin mechanism, not by an orbital effect. The spin mechanism operates at any orientation of the magnetic field but, according to our studies in the weakly localised regime,¹⁷ its contribution in the perpendicular geometry is partly compensated by an orbital effect. The latter was assigned¹⁷ to the destructive influence of the perpendicular component of the magnetic field upon the single-electron interference of self-crossing trajectories.^{1,2} Owing to the low mobility of the electrons in our structures, the interference effect compensate the positive magnetoresistance over a wider field range in Si/SiGe: Sb SLs than in high mobility Si-MOSFETs. It should be noted however that the actual nature of the metallic ground state in Si-MOSFETs is unknown.

It is worth comparing the behaviour of Si-based structures to materials with a much larger ratio of the cyclotron to Zeeman energy, such as n-GaAs. The effect of the field on the single-electron interference was shown to drive barely insulating n-GaAlAs to the metallic phase.²⁵ In sufficiently strong fields, in turn, a field-induced localisation is observed, which in the metallic n-GaAs/AlGaAs SLs occurs at smaller magnetic fields when the field is oriented *perpendicular* to the interface.²⁶ This suggests that an orbital effect, such as the diamagnetic lowering of the carrier kinetic energy by the magnetic field,²⁷ accounts for the MIT in n-GaAs-based systems.

A least-square fit to all data for the $\tilde{N} = 4.5$ sample between 100 and 500 mK in both parallel and perpendicular configurations was performed by the dependence $\delta\sigma(T) \propto T^{\alpha}$. As shown in Fig. 3, the exponent α is ≈ 0.2 at zero or weak magnetic fields, which can be compared with $\alpha = 1/3$, as found in a recent study of n-Ge near the MIT.²⁸ Between 0.5 and 1.5 T a nearly step like increase to $\alpha \approx 0.5$ takes place. In this region the spin splitting $g\mu_B B$ becomes greater than the energy of thermal broadening kT , and thus a cross-over to a different universality class is expected.^{3,15} A change of the universality class is also confirmed¹⁷ by replotting the experimental results between 0.8 and 1.4 T in coordinates suggested by the Finkelstein renormalization group approach^{3,15} for the MIT driven by the disorder-modified electron-electron interactions. Because of a strong dependence of σ on T our data are particularly sensitive to the value of the dynamic exponent z , and give $z = 1.6 \pm 0.2$ in the magnetic field. A similar analysis for bulk n-Si at $B = 0$ yielded $z = 3.1$,²⁹ while that for the MIT of spin-polarised electrons in diluted magnetic semiconductors resulted in $z = 1.7 \pm 0.4$.³⁰

The values of α and z quoted above indicate that n-Si

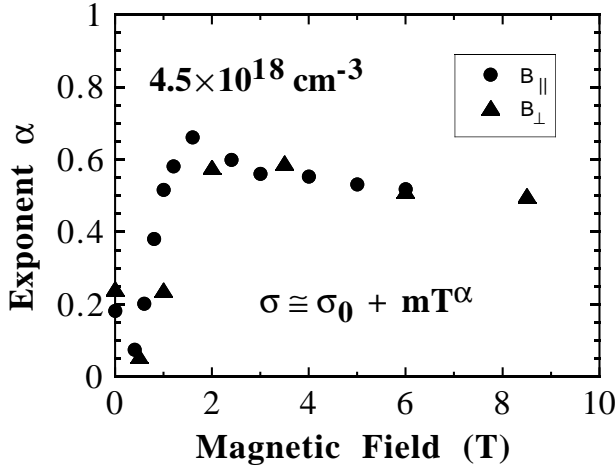


FIG. 3. Exponent α in the temperature dependence of conductivity $\delta\sigma(T) \propto T^\alpha$ for parallel (circles) and perpendicular (triangles) magnetic fields.

and n-Ge belong to the same universality class whereas diluted magnetic semiconductors³⁰ and n-Si in the magnetic field²² form another one. Since the electrons in the minority-spin band become localised and decoupled from the majority-spin carriers already on the metal side of the MIT, we suggest that the corresponding universality class is rather "spin polarised"^{30,31} than "strong magnetic field"^{3,15,31}.

In conclusion, the magnetic field-induced metal-insulator transition in Si/SiGe superlattice structures doped with Sb is observed for the magnetic field that is parallel to the SL interfaces. The absence of the transition in the case of the perpendicular magnetic fields shows rather directly that spin effects are crucial. The temperature dependence of the conductivity at criticality, together with detailed studies of the magnetoconductivity in the weakly localised regime,¹⁷ demonstrate that the dominant contribution comes from the anti-localising triplet diffusion term of the disorder-modified electron-electron interactions. We suggest that this term, perhaps together with the singlet cooperon contribution, plays also an important role in the high mobility Si-MOS structures, where an unexpected 2D-metallic state has been observed and shown to be destroyed by the parallel magnetic fields.

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